Determination of Ice Water Path in Ice-over-Water Cloud Systems Using Combined MODIS and AMSR-E Measurements

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Abstract

To provide more accurate ice cloud properties for evaluating climate models, the updated version of multi-layered cloud retrieval system (MCRS) is used to retrieve ice water path (IWP) in ice-over-water cloud systems over global ocean using combined instrument data from the *Aqua* satellite. The liquid water path (LWP) of lower layer water clouds is estimated from the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) measurements. With the lower layer LWP known, the properties of the upper-level ice clouds are then derived from Moderate Resolution Imaging Spectroradiometer measurements by matching simulated radiances from a two-cloud layer radiative transfer model. Comparisons with single-layer cirrus systems and surface-based radar retrievals show that the MCRS can significantly improve the accuracy and reduce the over-estimation of optical depth and ice water path retrievals for ice-over-water cloud systems. During the period from December 2004 through February 2005, the mean daytime ice cloud optical depth and IWP for overlapped ice-over-water clouds over ocean from *Aqua* are 7.6 and 146.4 gm^{-2}, respectively, significantly less than the initial single-layer retrievals of 17.3 and 322.3 gm^{-2}. The mean IWP for actual single-layer clouds was 128.2 gm^{-2}.

INDEX TERMS: 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 3359 Meteorology and Atmospheric Dynamics: Radiative process; 1620 Global Change: Climate dynamics.

1. Introduction

Distributions of ice cloud properties are needed to accurately characterize global hydrological and radiation budgets. Their estimation from satellites is often exacerbated by the presence of water clouds underneath the ice clouds. Satellite cloud retrieval techniques have typically relied on the assumption that all clouds are homogenous in a single layer, despite the frequent occurrence of overlapped cloud systems. Overlap can produce large errors in many retrieved cloud properties such as ice water path (IWP), cloud height, optical depth (τ), phase, and particle size. The influence of liquid water clouds and precipitation on the radiances observed at the top of the atmosphere (TOA) is one of the greatest impediments to accurately determining cloud ice mass for multi-layered systems with ice clouds above water clouds. The optical depth derived from the reflected visible radiance represents the combined effects of all cloud layers. When the entire reflected radiance is interpreted with an ice cloud model, the optical depth of the ice cloud can be severely overestimated because the underlying water cloud can significantly increase the reflectance. It is clear that the underlying clouds must be properly characterized for a more accurate retrieval from overlapped cloud systems.

Methods for direct retrieval of ice cloud properties using millimeter and sub-millimeter-wavelength measurements in all conditions [*Liu and Curry*, 1998, 1999; *Weng and Grody*, 2000; *Zhao and Weng*, 2002] have been developed but have seen only limited use. The discrepancy between cloud-top pressure derived from a CO_2-slicing retrieval and the IR-based cloud pressure has been exploited to detect overlapped clouds and retrieve the properties of each layer over a large portion of the Earth [*Chang and Li*, 2005a; 2005b]. These recent ventures into passive remote sensing of multi-layered clouds are encouraging, but the accuracy of these retrievals and their limitations are poorly understood.

Over ocean regions, the use of combined microwave (MW), visible (VIS), and infrared (IR) retrievals shows potential for improving multi-layered cloud retrievals. These retrievals have generally consisted of deriving the total cloud water path (TWP) by interpreting the entire cloud as either ice or water with the VIS and IR data, retrieving the liquid water path (LWP) with the MW data, and finally estimating the IWP as the difference between the two quantities. This approach has been implemented by combining data sets from different satellite platforms [*Lin and Rossow*, 1996; *Lin et al.*, 1998] and by using well-matched data on the same platform, e.g., the Visible Infrared Scanner (VIRS) and Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) data [*Ho et al*., 2003]. Recognizing that the radiances emanating from combined ice and water cloud layers are not equivalent to those from a simple addition of the IWP and LWP to obtain the TWP, *Huang et al.* [2005] developed a more rigorous multilayer cloud retrieval system (MCRS). The MCRS explicitly uses the lower layer cloud as part of the background radiation field and the ice-cloud contribution to the TOA radiance to estimate IWP. The initial version of the MCRS has been upgraded using reflectance lookup tables based on advanced radiative transfer calculations of combined ice and water clouds and applied to matched VIRS and TRMM data to obtain a more accurate assessment of tropical IWP [*Minnis et al*., 2006]. In the revised MCRS, the background in the two layer radiative transfer model is either a land or ocean surface. This enhanced version is more accurate and applicable to a broader range of boundary conditions.

In this study, the updated MCRS is applied to collocated CERES (Clouds and the Earth's Radiant Energy System) MODIS (Moderate Resolution Imaging Spectroradiometer) cloud products [*Minnis et al.*, 2004] and AMSR-E data to estimate IWP for multilayered clouds over global oceans. The MW-VIS-IR (MVI) algorithm [*Lin et al*. 1998] is used to identify the overlapped clouds. Then the ice cloud optical depth and ice water path, in ice-over-water cloud system, are retrieved from the MCRS. The IWP retrievals are further validated by comparison to millimeter wave cloud radar (MMCR) retrievals over the Atmospheric Radiation Measurement (ARM) Program tropical site on Manus Island [*Ackerman and Stokes*, 2003]. The variability and global distribution of IWP is further analyzed.

2. Data

The MCRS is applied to matched data from the MODIS and the AMSR-E on *Aqua* taken over water surfaces in daylight from December 2004 through February 2005. The 1-km MODIS data are analyzed for CERES using the VIS-IR-Solar-infrared-Split-window Technique (VISST) [*Minnis et al.*, 1995, 1998] to retrieve single-layer (SL) cloud properties for each pixel. The CERES MODIS (CM) cloud retrieval output [*Minnis et al.*, 2004], which includes cloud properties such as phase, cloud optical depth (τ), cloud effective temperature (Tc), effective ice crystal diameter (*De*) and IWP or LWP, is combined with the original MODIS radiances at 0.64, 2.1, 3.8, 10.8, and 12.0 µm for each pixel. The CM pixel-level results are then convolved into the AMSR-E footprints as in *Ho et al*. [2003]. The cloud LWP and cloud water temperature (Tw) are retrieved from the AMSR-E MW data at the 36.5-GHz 12-km field of view (FOV) by matching the multi-spectral MW data to MW radiative transfer model (RTM) calculations [*Lin et al.*, 1998].

3. IWP Retrieval

For each convolved CM-AMSR-E FOV, the MVI technique [*Lin et al.*, 1998] is used to detect overlapping clouds based on the difference between *Tw* retrieved from AMSR-E and *Tc* derived from VISST. The next step is to estimate the optical depth (τ_w) of the lower-layer water cloud, which can be written as

$$\tau_w = 0.75\, Q_{vis}(r_e)\, LWP/\, r_e, \qquad (1)$$

where

$$r_e = r_0 + r_1 * LWP, \qquad (2)$$

and $Q_{vis}(r_e)$ is the extinction efficiency for a given effective droplet radius (r_e). Over the ocean, r_0 =12 and r_1 = 0.0186. These values of r_e and then τ_w were derived from the statistical analysis of MVI-identified single-layer water clouds and are used to select the proper set of lookup tables (LUT). The TOA radiances are then computed for every combination of r_e and τ_w and upper-layer ice clouds and matched to the observed 0.64, 3.8, and 10.8-µm radiances as in *Minnis et al.* [2006]. The retrieval follows the VISST procedure resulting in the selection of *De*, τ, and *IWP* for the upper cloud.

4. Results

The MCRS was applied to retrieve ice cloud properties for the detected overlapped cloud pixels for the period from December 2004 through February 2005. *Minnis et al.* [2006] found good agreement between the updated MCRS IWP and millimeter cloud radar (MMCR) retrievals of the same quantity over Oklahoma. To further validate the MCRS retrievals, comparison of IWP derived from *Aqua* MODIS using VISST, from the convolved CM-AMSR-E data using the MCRS, and from the MMCR data using the algorithm of *Liu et al.* [2000] over ARM TWP Manus site (2.006°S, 147.425°E) were performed, see Figure 1. Sixteen matching cases were identified during the 3 months over the ARM TWP Manus site. The VISST and MCRS retrievals in Figure 1 are the averages for the pixels over the ocean surrounding the coastal Manus site. In all cases, the MCRS yields values of IWP that are close to those from the MMCR retrieval. On average, the MCRS and MMCR IWPs differ by only 16.1 gm^{-2} (9%). This difference is much smaller than the difference between the mean VISST (350.7 gm^{-2}) and mean MMCR (201.2 gm^{-2}) values and is probably within the error of the MMCR method and data, which were taken at a single point on the coast. It is clear from these results and earlier comparison that the MCRS provides a remarkable improvement over the VISST IWP retrieval.

Figure 2 shows a comparison of mean optical depth and standard error derived from the VISST and MCRS as a function of LWP for all overlapped cloud retrievals during the analysis period. The standard error gives a rough measure of the variability of the means. For the VISST retrievals, the optical depth increases linearly with rising LWP as expected because thin water clouds under the ice clouds should not cause large VISST retrieval errors [e.g., *Minnis* et al., 2006]. The reflectance increases with increasing LWP and causes the current satellite retrievals to overestimate τ when a lower-level cloud is present. The effects of the lower-level cloud, however, are nearly removed by the MCRS. There is only a slight upward trend in the MCRS τ associated with increasing LWP. On average, the mean ice-cloud optical depth drops from 17.3 to 7.6 when the lower-level water cloud is taken into account. Figure 2 also shows that the standard errors are quite small and the mean differences in τ are significant at the 99% level for all LWP bins.

The frequency histogram of IWP derived from VISST, MVI, and MCRS for ice-over-water clouds and the IWP derived from VISST for single-layer ice clouds is shown in Figure 3. As expected, the mean IWP values derived from the MCRS are considerably less than those derived from VISST. The mean IWP decreases from 322.3 gm^{-2} to 146.4 gm^{-2}, a value only slightly greater than the single-layer ice cloud mean value (128.2 gm^{-2}). The close agreement in the frequency distribution between IWP derived from the MCRS and those from VISST single-layer ice cloud retrievals, for all bins, clearly demonstrates the improvements provided by the MCRS. For the lowest category of IWP ($IWP < 100$ gm^{-2}), the frequency from the MCRS is only 10% more than the frequency determined for single-layer ice clouds. Multi-layered cloud pixels with IWP < 100 gm^{-2} comprise more than 65% of the data for the MCRS retrievals compared to only 38% for VISST retrievals. The mean MCRS IWP is roughly half of that from the VISST and, although the mean MVI IWP is only 17% greater than the MCRS value, it is obtained by the retrieval of significant amounts of negative IWP values. The MCRS also eliminates the generation of negative values of IWP.

The global distribution of the seasonal (December 2004 - February 2005) mean IWP derived from VISST and MCRS and the differences between them are shown in Figure 4. The seasonal means were only computed for overcast ice-over-water clouds. Thus, these results are a subset of the entire VISST dataset. Figure 4 indicates that the MCRS improves the IWP retrieval over all global oceans. For almost all of regions, the IWP derived from the MCRS is less than the VISST derived values. The IWP is found to be most pronounced, with VISST values up to 500 gm^{-2}, in the 40° - 60° latitude bands where baroclinic systems are common (Fig.4a and 4b). The major difference between VISST and MCRS (Fig. 4c) is also found in those same zones. In the

Southern Hemisphere, these large IWP means are nearly continuous throughout the temperate zone, while in the Northern Hemisphere, they are confined primarily to the western sides of the oceans. A relative maximum difference follows the northward shift of the inter-tropical convergence zone (ITCZ) where both thin cirrus and thick anvil clouds generated by deep tropical convection are frequently observed.

5. Conclusions and Discussion

Large-scale satellite retrievals are critical for both verifying and improving general circulation model (GCM) parameterizations of clouds and radiation for climate prediction. The global distribution of IWP, while available from a variety of current satellite analyses, is highly uncertain because of the bias caused by the presence of liquid water clouds under the ice clouds. *Chang and Li* [2005a] addressed this issue with a combined VIS-IR-CO_2 slicing technique that is nominally applicable over all surfaces, however, their method requires that the upper-layer cloud is optically thin. This study has provided an improved estimate of IWP in multi-layered cloud systems for both thin and thick non-precipitating ice cloud systems over ocean surfaces. The MCRS attempts a more realistic interpretation of the radiance field than earlier MVI-like methods because it explicitly resolves the radiative transfer that would produce the observed radiances at all relevant wavelengths. Using the MCRS to derive IWP in overlapped cases represents a first step toward constructing a more reliable global IWP climatology. Based on comparisons with the MMCR retrievals for multi-layered clouds and with VISST retrievals for single-layer ice clouds over the global oceans, these initial results are very encouraging. The development of an accurate oceanic climatology of IWP from *Aqua* and TRMM data is now quite feasible.

In the short term, this method will be extremely valuable for climate research by providing more accurate retrievals of IWP than previously possible. Future research should develop an advanced retrieval method for multi-layered clouds over land. Over land, the variability in surface emissivity renders the microwave approach nearly useless. Thus, surface radiometers like those at the ARM sites are the only data source for application of this technique. With further validation against radar retrievals and perhaps in situ aircraft data, this method could be used as reference source for other available techniques or for those under development which use other spectral radiance combinations. Because this technique does not require the presence of cloud radar, and may be applied at any location with a microwave radiometer, it provides the opportunity for validating other methods in many more conditions than possible using radar retrievals. Ultimately, it could be combined with methods like the VIS-IR-CO2 technique to provide a comprehensive characterization IWP over the entire globe.

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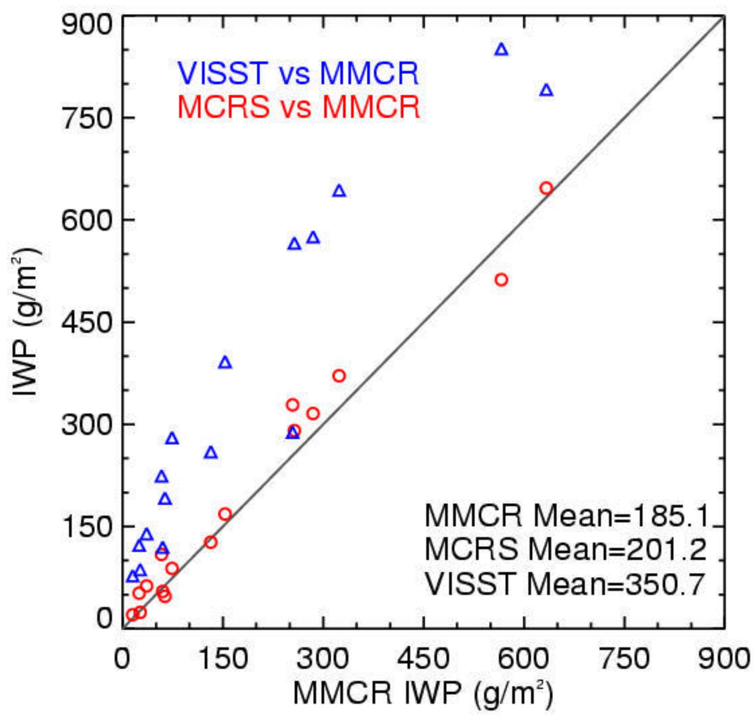
Figure Caption

Figure 1. Comparison of VISST and MCRS retrievals with simultaneous retrievals using the MMCR data the ARM Manus site (December 2004 - February 2005).

Figure 2. Comparison of optical depths derived from VISST and MCRS as a function of LWP for ice-over-water cloud pixels over global ocean (December 2004 - February 2005). The vertical bars are the standard errors ($s / \sqrt{N}$, where s is the standard deviation and N is the number of FOVs).

Figure 3. Histograms of IWP derived from VISST, MVI and MCRS for ice-over-water clouds, and IWP derived from VISST for single-layer ice clouds over global ocean (December 2004 to February 2005).

Figure 4. Global distribution of seasonal (DJF) mean IWP derived from *Aqua* data using (a) VISST and (b) MCRS, and (c) the difference between VISST and MCRS means.



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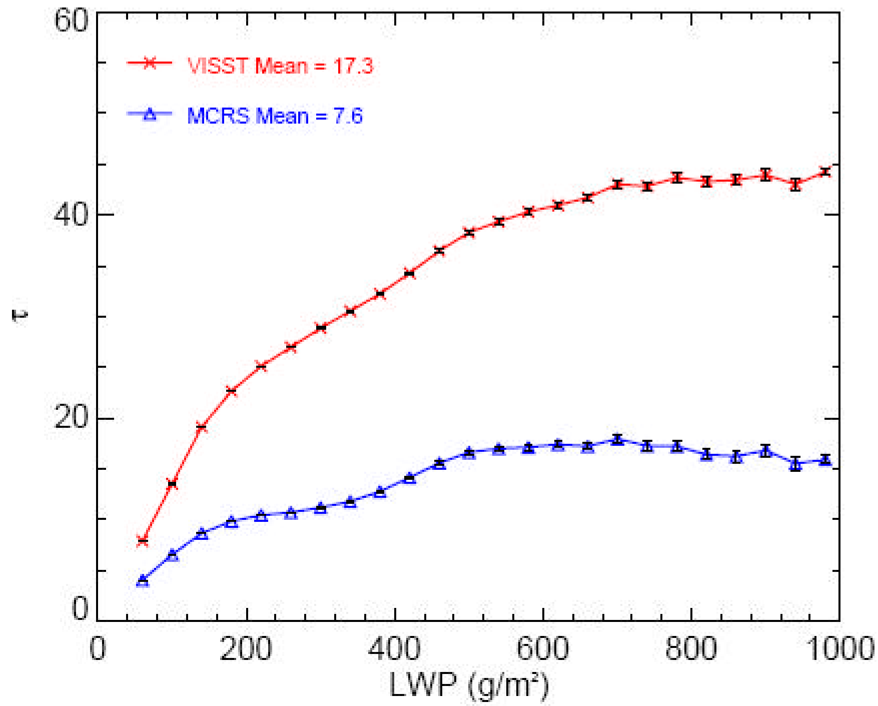

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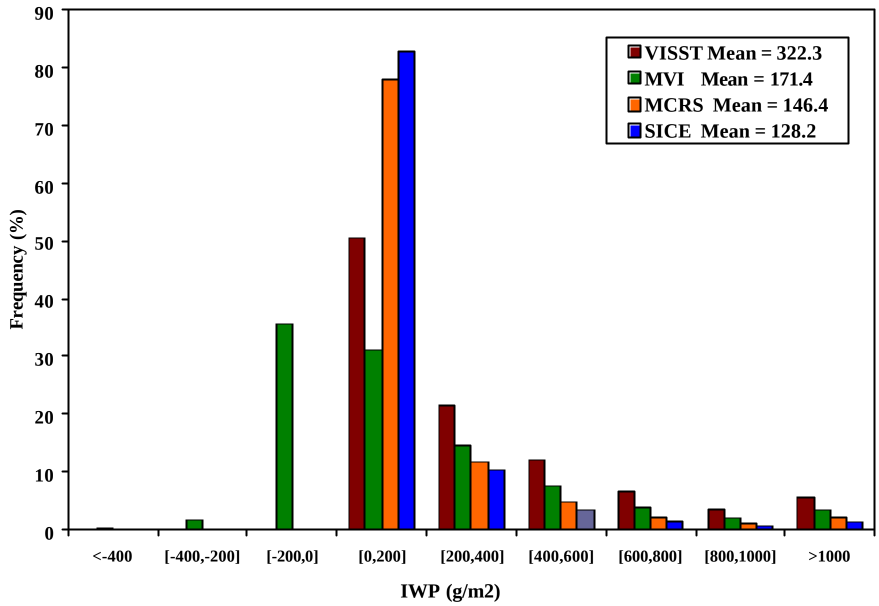

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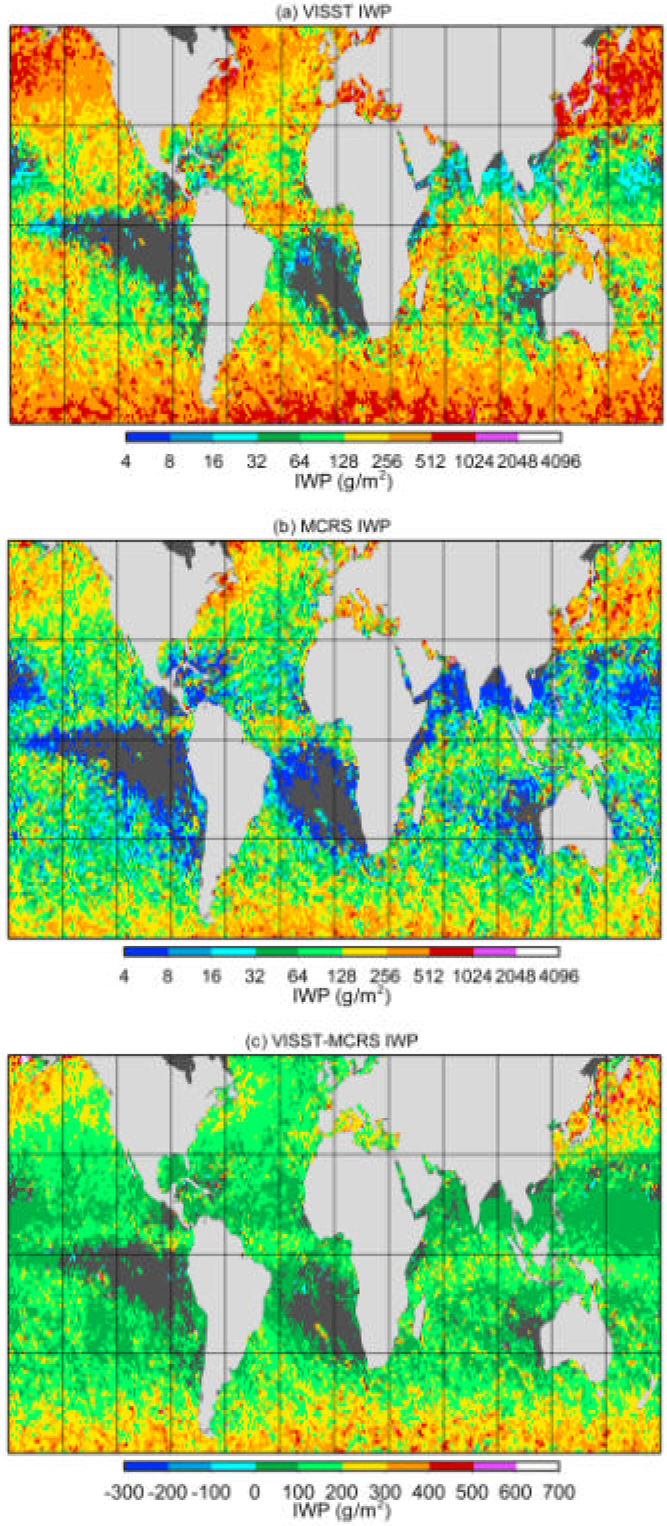

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